J Appl Electrochem (2014) 44:543–550
DOI 10.1007/s10800-013-0639-x

RESEARCH ARTICLE

Hybrid energy storage system based on supercapacitors and Li-ion batteries

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Received: 1 August 2013 / Accepted: 15 October 2013 / Published online: 25 October 2013

Abstract Energy storage systems (ESS) have a wide spectrum of functions. They must provide power quality, shaving of load change, coordination of distributed power systems, bulk energy storage, and end-user reliability, e.g., uninterrupted power supply. In present paper the configuration and design of experimental ESS based on both Li-ion batteries and supercapacitors have been proposed. Such a hybrid energy storage system (HESS) includes three main components: Li-ion batteries, supercapacitors, and grid interconnection consisting of two invertors and control and monitoring system. Energy storage capacity of developed HESS prototype is 100 kWh, nominal power—100 kW, peak power—200 kW. HESS was created and tested within the experimental facility also including 1.5 MW gas turbine power plant, 200 kW controllable active and reactive loads, and control and measurement system. Experimental results showed that HESS successfully provides the following advantages: (i) suppression of voltage, current, and frequency disturbances in the grid; (ii) compensation of reactive power in the circuit; and (iii) uninterrupted power supply. Cost analysis of proposed hybrid system has also been carried out. In comparison with battery ESS without supercapacitors, HESS showed longer life time, lower cost, and higher peak power.

Keywords Energy storage · Hybrid · Li-ion battery · Supercapacitor · Micro grid · Smart grid

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1 Introduction

Electricity is a universal clean energy carrier. Electric energy solves a wide variety of vital problems of modern civilization. But one of the features of electric energy is its storage inconvenience. That is why the problem of the development of effective systems for electric energy storage is an evergreen issue. Recently a wide range of storage devices has been developed based on various principles differentiated by both performance characteristics and operational principle: hydraulic and pneumatic accumulators, flywheels, superconducting magnetic energy storage devices, capacitors, and various electrochemical storage systems [1, 2].

An interest to energy storage problem in future will substantially grow due to increasing interest to the development of intellectual electric energy systems—Micro Grids and Smart Grids [3]. One of the key elements of intellectual grids is energy storage system (ESS), which can provide a number of important functions:

– bulk energy storage for load-leveling (with several hours of continuous discharge);
– enhancement of transmission capacity;
– voltage, frequency, VAR, or phase angle regulation;
– power quality improvement: suppression of disturbances such as instantaneous voltage sags or power disconnection (with the duration of upto seconds).
– reliability and load peak shaving (e.g., for renewable energy sources);
– uninterrupted power supply (UPS): end-user reliability (with the duration from seconds to hours).
– Storage devices based on high-capacity batteries have a number of advantages:
– modular design, relatively compact size;

- functional flexibility;
- easy control and maintenance;
- simple integration into Smart Grids.

These advantages are confirmed for example by successful operation of megawatt-scale battery storage system based on sodium-sulfur batteries manufactured by NGK Insulator, Xcell Energy etc. [4]. Main drawbacks of storage devices based on sodium–sulfur batteries are high self-discharge current and low energy density. For some ESS applications these drawbacks turn out to be essential.

Such drawbacks are minimized in case of ESS developed on the basis of Li-ion batteries. That is why at present time ESS of this type is of especial interest. However, up to now, only few dozens of large-scale ESS based on Li-ion batteries have been manufactured and generally they are in the mode of experimental operation. It is clear that large-scale Li-ion batteries have a number of unsolved problems, e.g.:

- high specific cost of stored energy;
- insufficient cycle life (500–3,000 charge/discharge cycles);
- significant decrease of cycle life at high charge/discharge current;
- problem of depth discharge.

To solve problems mentioned above, we proposed the Hybrid Energy Storage system (HESS) adding supercapacitors to Li-ion batteries. To verify main ideas of our proposal we designed and created the prototype of HESS with 100 kWh energy storage capacity and 100 kW nominal power. Functional characteristics of created HESS were studied during experimental research.

2 The purpose of the hybridization

The essence of hybridization is in combined use of batteries and supercapacitors. This approach is well known in transportation, but is relatively new in stationary applications [5–7]. A battery possesses acceptable energy capacity (for Li-ion systems—90–150 Wh/kg), but relatively small cycle life (500–3,000 charge/discharge cycles). Moreover, battery operation at high power strongly decreases its specific energy and cycle life.

Supercapacitor has low specific energy (1–5 Wh/kg), but its cycle life is significantly longer—upto 1,000,000 charge/discharge cycles. Supercapacitor is relatively insensitive to high currents. At given output voltage its maximum power is determined by circuit impedance only. A combination of batteries and supercapacitors in common storage system can provide grid disturbance suppression in a wide range of disturbance durations. Supercapacitors without battery

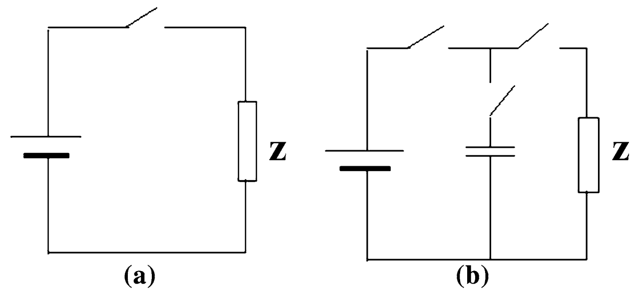

Fig. 1 Layouts of storage systems. **a** battery EES; **b** HESS based on battery and supercapacitor. More flexible HESS functionality is symbolically illustrated by closed and opened keys with different combinations

suppress the disturbances with the duration of upto 1 min. At the disturbance duration from a minute upto several hours, battery part of storage system is intended. Moreover, the presence of supercapacitors in HESS allows shaving peaks of power at charge or discharge mode of battery thus elongating its cycle life. Simultaneous discharge of batteries and supercapacitors can provide the significant increase of peak output power, but the duration of peak regime is limited by discharge time of supercapacitor. Operation principles of both battery ESS and HESS are illustrated in Fig. 1.

Figure 2 shows the dependence of power cost [Cost (P,n)] of different ESS on its time of continuous operation (t). Exactly, this time is time of discharge and it determines the energy capacity of ESS. Three types of ESS have been estimated: batteries (dashed line with the biggest angle of slope in Fig. 2), supercapacitors (dashed line with the smallest angle of slope in Fig. 2) and HESS (solid lines between dashed lines). HESS type was considered in three combinations of energy capacities of battery and supercapacitor (labeled in Fig 2 as $k = 1, 2, 50$). Estimations were based on the following equation:

$$\text{Cost }(P,n) = t_{sc}C_{sc}/n_{sc} + C_{batt}(t - t_{sc})/n_{batt},\ \text{USD}/\left(\text{kW} \times n_{cycles}\right)$$

or;

$$\tag{1a}$$

$$\text{Cost }(P,n) = t/k \times [C_{sc}/n_{sc} + C_{batt}(k-1)/n_{batt}],\ \text{USD}/\left(\text{kW} \times n_{cycles}\right) \tag{1b}$$

where, P is the power of the ESS; N the maximum number of charge/discharge cycles of the ESS; t the time of continuous operation until the complete discharge (ESS energy capacity is calculated by multiplication of time (t) with average power in discharge cycle); t_{sc} the time of continuous operation of the supercapacitor part of HESS, hours; C_{sc} the specific cost of supercapacitor, USD/Wh; n_{sc} the maximum number of charge/discharge cycles of supercapacitor (cycle life); C_{batt} the specific cost of battery, USD/

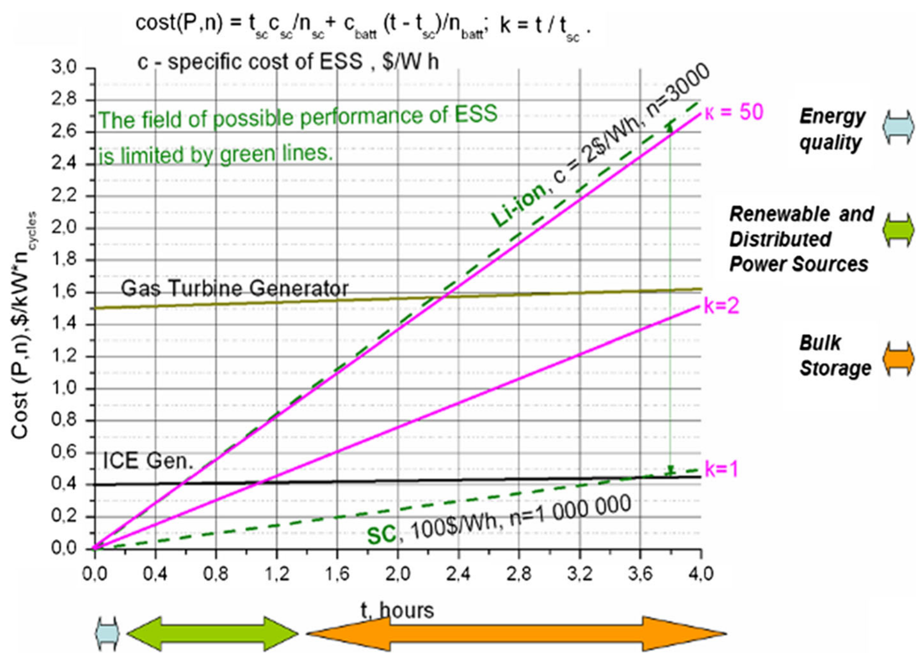

Fig. 2 Specific costs of battery, supercapacitor, and hybrid storage systems depending on time of continuous operation (capacity). $k = t/t_{sc}$ is a ratio of maximum time of continuous discharge of HESS (t) to the maximum time of continuous discharge of the supercapacitor part of HESS (t_{sc}). Gas Turbine Generator and ICE Gen lines—specific costs of gas turbine power plant and internal combustion engine power generator. n is a maximum amount of charge/discharge (start/stop) cycles for a corresponding storage system (generator)

Wh; n_{batt} the maximum number of charge/discharge cycles of battery (cycle life); and $\kappa = t/t_{sc}$ the hybridization parameter—the ratio of (t) to (t_{sc}).

The same estimations were carried out for internal combustion engine generator (ICE Gen) and gas turbine (GT) power plant. The results of such estimations are shown in Fig. 2 as well. A small slope of corresponding curves is explained by taking into account the cost of fuel (natural gas). Cost(P,n) for generators was estimated by the following equation:

$$\mathrm{Cost}(P,n)\ \mathrm{ICE\ Gen} = \mathrm{Cost}(P)_{\mathrm{ICEG}}/n_{\mathrm{ICEGen}} + \mathrm{Costf}t/n_{\mathrm{ICEGen}} \times \eta_{\mathrm{ICEG}} \tag{2}$$

where $\mathrm{Cost}(P)_{ICEG}$—specific cost of ICE, USD/kW, $n_{ICE\text{-}Gen}$—number of start/stops cycles of ICE generator and GT power plant up to an overhaul, cost_f—fuel cost (natural gas cost), η_{ICEG}—engine efficiency.

Figure 2 demonstrates that the application of ESS based on Li-ion batteries is economically profitable in comparison with ICE if ESS discharge time (ICE operation time) does not exceed an hour and it is economically profitable in comparison with GT if ESS discharge time (GT operation time) does not exceed 2 h. The same comparison with ESS based on supercapacitors gives significantly longer times in accordance with significantly longer cycle life of supercapacitor. It means that ESS based on supercapacitors is principally cheaper than ESS based on Li-ion battery. As hybridization parameter k increases, power cost—Cost (P,n)—decreases.

At the same time it should be taken into account that specific energy of supercapacitors is 20–100 times lower than that for batteries. Thus, the creation of supercapacitor storage system with high energy capacity would look like engineering nonsense. Such ESS would be too large and heavy. On the contrary, the hybridization (parameter k in Fig. 2) allows to optimize the ESS by varying its cost and mass-dimensional characteristics depending on functional requirements. The possibility of such optimization is the important advantage of hybrid scheme.

The final choice of the hybridization parameter defines the concrete field of applications. The detailed reviews of possible applications of EES and durations of disturbances occuring at different applications of storage systems are presented in [8].

The aim of the present development was to provide suppression of grid disturbances of short and medium durations—regions labeled by blue and green arrows in Fig. 2. The second aim was to defend a battery from sharp jumps of charge/discharge current.

The maximum duration of short range disturbances in real grid conditions was estimated by 10 s. The maximum duration of medium range disturbances was defined by 1 h. At rated power of HESS 100 kW it gives hybridization parameter $k = 360$. Of course, this value of k does not give

any real cost profit, but allows to minimize the system size and to investigate general operation features of HESS.

3 HESS-100 description

The prototype of hybrid energy storage system HESS-100 consists of three main modules: (i) Li-ion battery module (LBM); (ii) supercapacitor module (SCM); and (iii) grid interconnection (GI), including two individual invertors for LBM and SCM and control and monitoring system (CMS).

LBM stores the electrical energy when load is low and returns it to the grid when load exceeds defined value. LBM consists of 168 LiFePO4 cells manufactured by LLC SSK Group. LBM's management system provides the following functions: (i) voltage balancing of separate cells; (ii) cells switching and their current protection; and (iii) insulation control.

SCM is intended for compensation of short duration (upto 10 s) disturbances in the grid and for shaving the peaks of charge/discharge current of the batteries. It consists of twenty supercapacitors manufactured by JSC "TECHNOCOR". Capacity of each supercapacitor is 0.93 F, voltage is 360 V, and mass is 38 kg.

GI consists of two similar inverters: one works with LBM, another—with SCM. Inverters represent bidirectional DC/AC inverters which also provide voltage matching and independent control of active and reactive power. GI includes also CMS and with its help manages the HESS-100 and filters the noise in the grid. GI improves the quality of electrical energy due to the use of algorithms of compensation of main harmonic and harmonics closed to main. It also stabilizes the output current when overload is occurred.

For coordination of operation of two similar inverters, and for elimination of parasitic power flows the GI of Li-ion battery operates in "master" regime forming the management commands for the GI supercapacitor module. The latter one operates in "slave" regime. Such commutation scheme allows to implement the management algorithms for the entire system as well as for its separate elements.

The operational algorithms realized in the management system of HESS-100 provide recognition of character and parameters of disturbance, formation of control laws required for supression of the disturbances. HESS-100 operational algorithms include the supplementary procedures such as: monitoring and measurement of all subsystems states, control of the state of charge, control of set of procedures for maintaining of pre-set conditions, and operational safety.

Electrical scheme of HESS-100 is shown in Fig. 3. Main performance characteristics of HESS-100 are presented in Table 1.

The real-life views of HESS-100 modules are shown in Fig. 4.

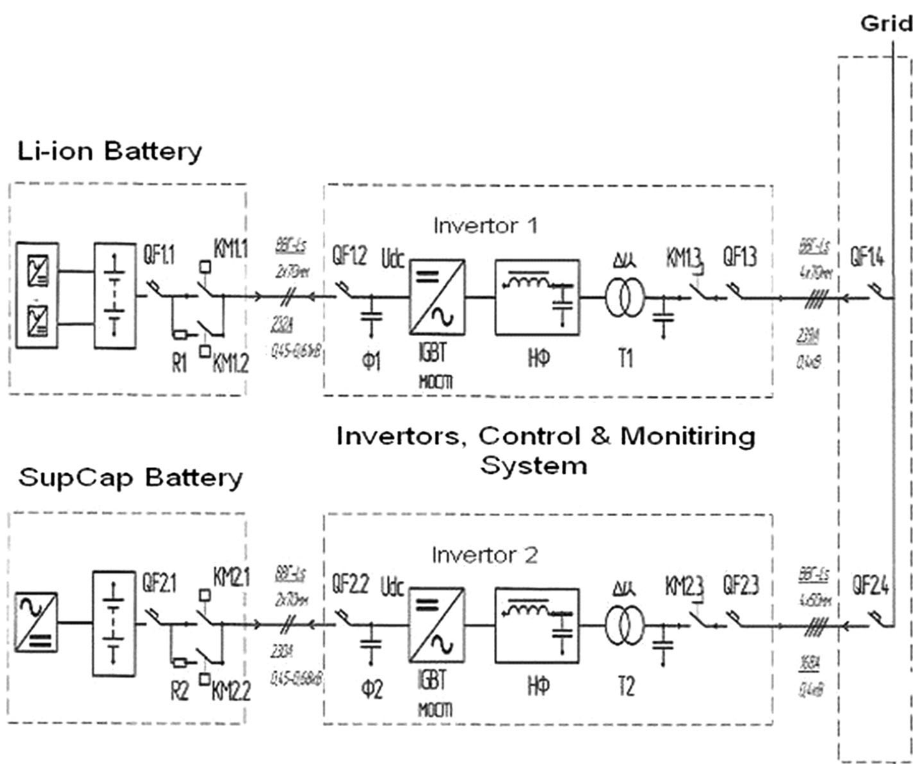

Fig. 3 Electrical scheme of HESS-100

Table 1 Main performance characteristics of HESS-100

Nominal power, kW	100
Peak power, kW	200
Nominal voltage (3-ph, 50 Hz), kV	$380^{+10\%}_{-15\%}$
Output phase current, A	152
The range of direct voltage, V	430…820
Current harmonic factor, no more than, %	7
Energy storage, kWh	100
Operation time at current overload, s	10
Operation time at nominal power, h	1.0
Reactive power variation ranging, kVAR	(0 ÷ 100)
Efficiency of charge/discharge cycle, no less than,	75
Baud rate of RS-485, kbit/s	56
Baud rate of CAN, kbit/s	250
Cycle life, no less than, charge/discharge cycles	1500
Operational life, not less than, years	10

4 Experimental

Experimental study of main functional characteristics of HESS-100 was carried out on specially developed test bench consisted of the following subsystems:

– gas turbine power plant (GT-1500) with the voltage of 6.3 kV and nominal power of 1,250 kVA;
– 6.3 kV/0.4 kV step-down transformer;
– the set of active loads with total power of 200 kW;
– the set of reactive loads with total power of 65 kVAR;
– voltage, current and frequency measurement system.

Test bench looked like the micro grid because it included all parts related to micro grid: power source (GT-1500), energy consumer (the set of loads), energy storage units, and control and management system. Disturbances of different magnitudes and durations were created by means of loads commutations. CMS protective devices were

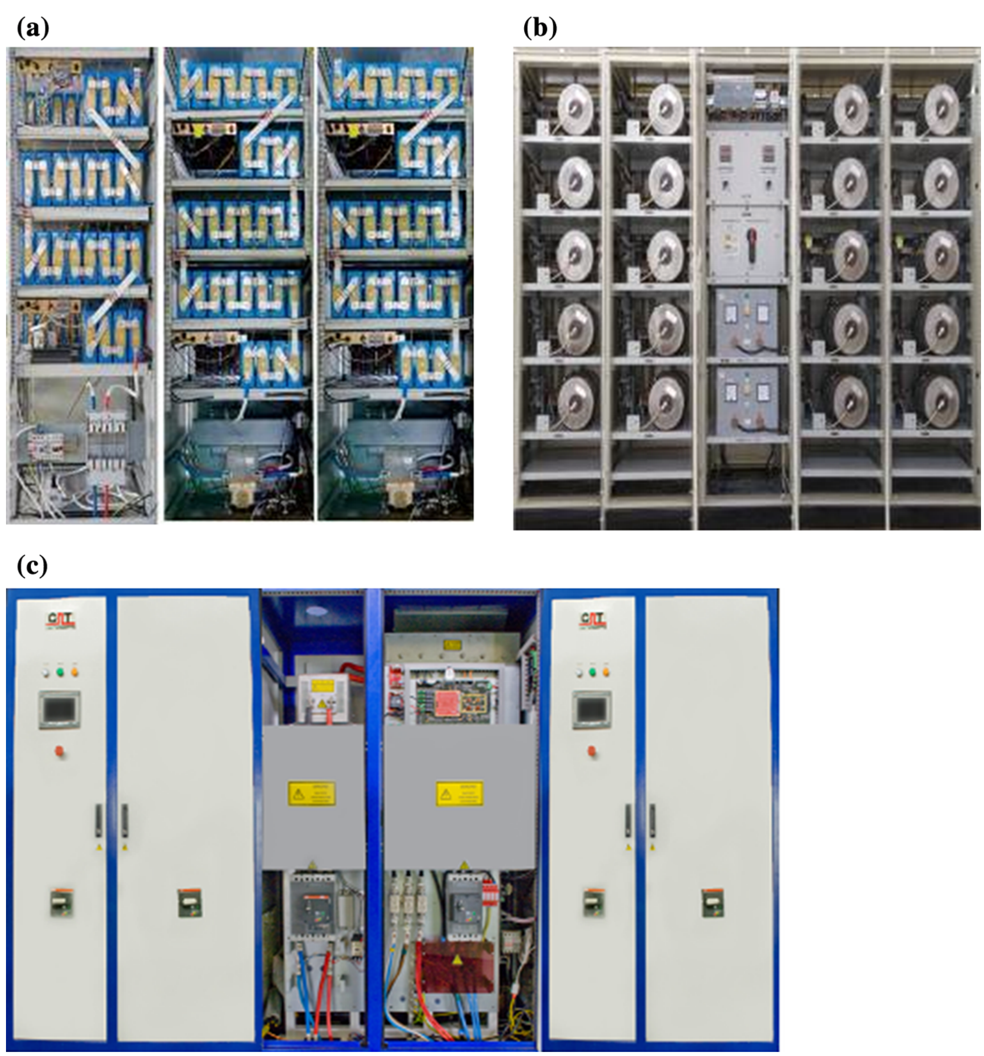

Fig. 4 Real-life views of HESS-100 modules: **a** Li-ion battery module (LBM); **b** supercapacitor module (SCM); and **c** grid interconnection (GI)

intended for the protection of loads switching and for inadmissibility of micro grid elements overload and shirt-circuit currents.

LBM and SCM were tested during experimental study both as separate energy sources and in combined (hybrid) regime.

The tests were carried out in the following operation modes:

Autonomous discharge of HESS This mode assumes that power source is turned off and only HESS-100 supplies power to the set of loads. In this case GI of HESS-100 operated as a source of voltage, forming amplitude, frequency, and phase of voltage into the grid.

Suppression of power and frequency disturbances This mode was aimed to study the good of HESS applying in suppression of disturbances created by load increasing/decreasing. Disturbances were created by means of loads commutations and were suppressed by HESS-100. Experiments were carried out with the aim of study the efficiency of suppression by the investigation of frequency spectrum of suppression process. During the experiments the amplitude, frequency and phase of voltage, and current were measured.

Compensation of reactive power It was assumed that HESS can compensate ±100 % of reactive power generated in the grid. The aim of experiments in this mode was the verification of this assumption.

Uninterrupted power supply (UPS). One of the invertors is used for the transmission of electric power from the ac grid to dc link to which LBM and SCM are connected. Another inverter performs the reverse transformation from dc link to the load thus securing the consumer (load) against power source interruption. Thus UPS mode was realized. The set of loads was powered uninterruptedly in case of power source disconnection due to HESS-100 connection. Time of continuous operation of HESS-100 in UPS mode was limited by its energy capacity to the moment of interruption.

Experimental results obtained during the tests of HESS-100 in some of above listed modes are shown in Figs. 5, 6, 7.

Figure 5 shows that each switching was accompanied by a short pulse of current and power. Amplitude and duration of these pulses were defined by the accuracy of HESS-100 tuning. The presented tuning was adjusted for the demonstration of suppression process.

Figure 6a shows that if HESS-100 was not activated, the commutation of the load led to the frequency surges. In an approximately 100 ms every frequency surge was suppressed by the frequency compensation system of power source (power plant GT-1500). Figure 6b shows that with

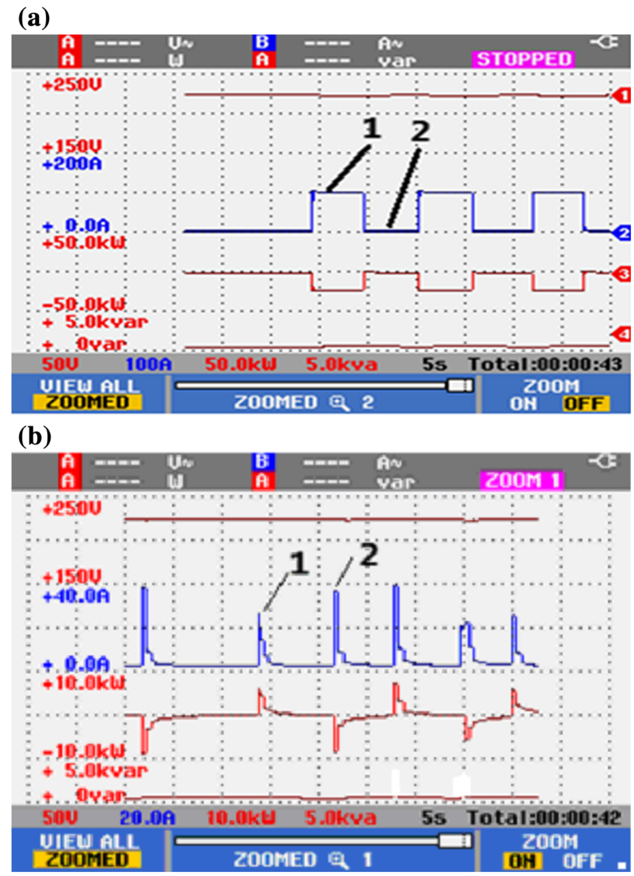

Fig. 5 **a** Suppression of power disturbance is absent. *Plateau 1* load is switched on (100A, 25 kW); *plateau 2* load is switched off. *Red curve*, *channel 1* grid voltage; *blue curve*, *channel 2* generator current; *red curve*, *channel 3* generator power; *red curve*, *channel 4* reactive power (equal to zero in this record). **b** Suppression of power disturbances. *Peak 1* load is switching off; *peak 2* load is switching on. *Red curve*, *channel 1* grid phase voltage = 220 V; *blue curve*, *channel 2* generator current; *red curve*, *channel 3* generator power; *red curve*, *channel 4* reactive power (equal to zero in this record)

the help of HESS-100 the surges of frequency are suppressed at the same commutation of the load.

Figure 7 shows that after the ac grid shutdown, HESS-100 smoothly recovered the voltage on the load. The time of recovery is defined by the GI tuning and may be changed in the range of 20–1,000 ms.

Experimental results demonstrated generally the following:

1. The change of load with the period of 1, 2, 5, and 10 s within the power range of 0–100 kW may be compensated by SCM without of LBM.
2. When period between the changing of load within the power range of 0–100 kW is more than 10 s the stabilization of active and reactive power in the grid is provided by means of batteries.

(a)

(b)

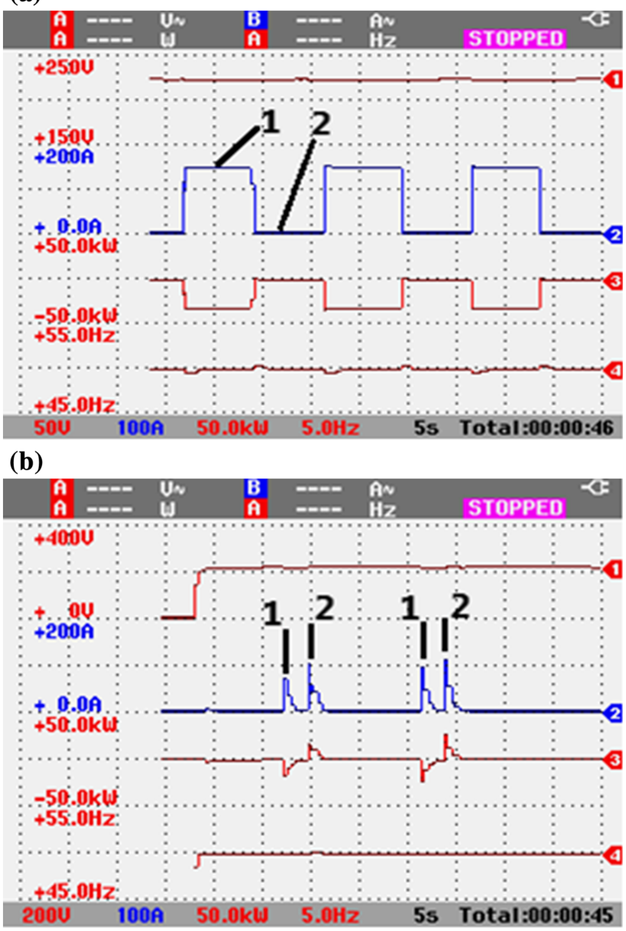

Fig. 6 **a** Suppression of frequency disturbance is absent. *Plateau 1* load is switched on; *plateau 2* load is switched off. *Red curve*, *channel 1* grid phase voltage = 220 V; *Blue curve*, *channel 2* generator current; *red curve*, *channel 3* generator power; *red curve*, *channel 4* current frequency. **b** Suppression of frequency disturbance. *Peak 1* load is switching off; *peak 2* load is switching on. *Red curve*, *channel 1*—grid phase voltage = 220 V; *Blue curve*, *channel 2* generator current; *red curve*, *channel 3*—generator power; *red curve*, *channel 4* current frequency

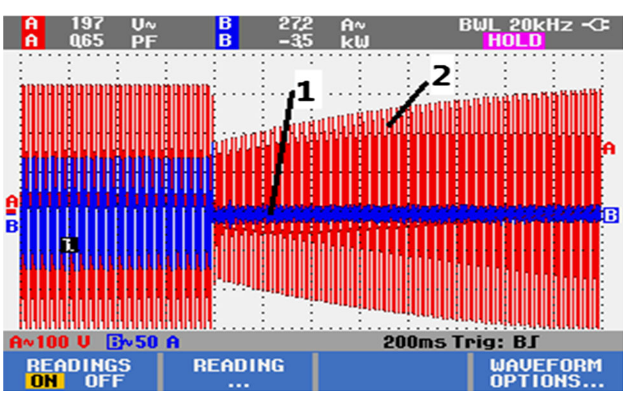

Fig. 7 UPS mode. *Blue curve*, marked as 1, *channel B*—grid current. *Red curve* marked as 2, *channel A*—load voltage

3. Therefore, during periodical change of load with the period of 1, 2, 5, 10, and 100 s within the power range of 0–100 kW HESS provides the stabilization of active and reactive power in the grid. The disturbances with high-frequency spectrum (with the period of less than 10 s) are suppressed by SCM, and the disturbances with low-frequency spectrum (with the period more than 10 s) are suppressed by LBM.
4. Experiments in UPS mode showed that HESS provides uninterruptible power supply of consumer and maintains the constant level of voltage and power on the load.
5. HESS-100 can provide short-period double increase of power (upto 200 kW) by means of simultaneous discharge of batteries and supercapacitors.

5 Conclusions

HESS based on combined using of Li-ion batteries and supercapacitors was proposed for the development of high-power high-energy capacity electrochemical ESS for stationary applications. It was shown that such hybridization allows decreasing the cost and increasing the cycle life of ESS.

The prototype of HESS was developed and tested. Energy capacity of prototype (HESS-100) is 100 kWh, nominal power—100 kW, and peak power—200 kW. Experimental results showed that HESS successfully provides the following functions:

- suppression of disturbances of active and reactive power;
- frequency stabilization;
- uninterrupted power supply.

Additional advantages of hybridization, which were confirmed in this study are the following:

- charge and discharge currents of Li-ion batteries increase and decrease more gradually in case of hybridization than in case when Li-ion batteries operates without supercapacitors. More gradual charge/discharge current changing is certain to soften the operation conditions of batteries;
- short-duration disturbances may be suppressed by HESS with the help of SCM only (without LBM using);
- HESS allows realizing short-period peak power regime due to simultaneous discharge of batteries and supercapacitors;
- SCM allows stabilizing reactive power in the grid.

HESS design provides its functional flexibility. HESS is well adapted for a wide spectrum of energy storage and

grid management applications including Smart Grid and Micro Grid.

In a hybrid energy storage system the presence of supercapacitors allows shaving peaks of power at charge and discharge mode of battery. We believe that this feature of HESS must elongate the life time of batteries and thus increase the life time and reliability of whole system. In this study we did not conduct resource tests. Nevertheless we hope to carry out the experimental study of reliability and life time performance of HESS in the nearest future.

Acknowledgments The authors would like to thank Dr. Pavel Mogilevsky of UES Inc. for reviewing the manuscript and useful discussions. The study was conducted under the Government Contract of Ministry of Education and Science of Russian Federation No. 14.516.11.0064 and under the contract of Federal Grid of System of Unified Energy System D 2045-11.

References

1. Schoenung SM, Hassenzahl W (2007) Long vs. short-term energy storage: sensitivity analysis. A study for the DOE Energy storage systems program. Sandia Report. SAND2007-4253. Unlimited release printed July 2007
2. Molina MG (2012) Distributed energy storage systems for applications in future smart grids. Transmission and Distribution: Latin America Conference and Exposition (T&D-LA), 2012 Sixth IEEE/PES. doi: 10.1109/TDC-LA.2012.6319051
3. (2011) Electrical energy storage. White paper. International electrochemical commission
4. Norris BL, Newmiller J, Peek G (2011). NAS® battery demonstration at american electric power. A study for the DOE Energy storage program. Sandia Report. SAND2006-6740. Unlimited release printed March 2007
5. Zhuk AZ, Kleymenov BV, Sheindlin AE et al (2011) Combined power plant based on an air–aluminum electrochemical generator for transportation purposes. Therm Eng 58:1154–1161. doi:10.1134/S0040601511140102
6. Guoju Z, Xisheng T (2010) Research on battery hybrid storage and its application in MicroGrid. Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific. doi: 10.1109/APPEEC.2010.5448231
7. Ongaro F, Saggini S, Mattavelli P (2012) Li-ion battery-supercapacitor hybrid storage system for a long lifetime, photovoltaic-based wireless sensor network. IEEE Transaction on power electronics 27:3592–3944. doi:10.1109/TPEL.2012.2189022
8. Eyer J., Corey G. Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment. Sandia Report. SAND2010-0815. 2010